# PV array connected to the grid with the implementation of MPPT algorithms (INC, P&O and FL method)

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**ABSTRACT**

The purpose of this article is to extract the maximum power point at which the photovoltaic system can operate optimally. The system considered is simulated under different irradiations (between 200 W/m$^2$ and 1000 W/m$^2$), it mainly includes the established models of solar PV and MPPT module, a DC/DC boost converter and a DC / AC converter. The most common MPPT techniques that will be studied are: "Perturbation and Observation" (P&O) method, "Incremental Conductance" (INC) method, and "Fuzzy Logic" (FL) control. Simulation results obtained using MATLAB/Simulink are analyzed and compared to evaluate the performance of each of the three techniques.



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## 1. INTRODUCTION

Renewable energy sources (RES) are part of the energy transition as a substitute for fossil fuels; they are the subject of renewed interest in recent years. Photovoltaic solar energy is among the renewable energies with the greatest potential for development, it attracts human attention because of its clean energy, cost reduction, continuity and reliability. However, the variation of power generation with atmospheric conditions is the major challenge of photovoltaic system applications and it's the main issue that must be taken in consideration. So, it is crucial to increase the efficiency of the photovoltaic (PV) system which should operate at the maximum power point [1]. However, the power generated by these panels varies continuously varying with weather conditions, which makes the power conversion efficiency very low (only about 15% of the energy converted by sun's light becomes electricity) [2].

More so, environmental factors such as solar radiance and ambient temperature significantly determine the energy amount that can be produced. Thus, an adequate MPPT is required by the control unit to reach the maximum power generated from the output PV array [3]. Several MPPT algorithms are proposed in the literature; some well-known are Perturb and Observe (P&O), the Incremental Conductance (INC), Fractional open-circuit voltage (FVOC), Fractional short circuit current (FSC), artificial neural networks (ANN), Fuzzy logic (FL), etc [4-7].

Comparing the performance of these techniques seems a very interesting spot to determine which one is most suitable and efficient for a given PV system [8]. The purpose of the present paper is to study and

compare the most appropriate maximum power point tracking (MPPT) methods for photovoltaic applications and assess their performances under irradiation changes using Incremental conductance method, Perturb and Observe method and Fuzzy Logic Control method.

A simulation study is designed to establish an implementation of 3 MPPT algorithms for PV modules connected to the electrical grid, giving a satisfactory response to the irradiation changes problem using MATLAB/Simulink software.

## 2. MODELING OF THE PV SYSTEM

The main elements of the solar photovoltaic system are grouped into five blocks as shown in Figure 1. It consists of a PV module, a DC/DC converter whose role is to make an impedance adaptation to ensure maximum energy independent of weather and load variations, a VSC converter, a three-phase transformer and a control system.

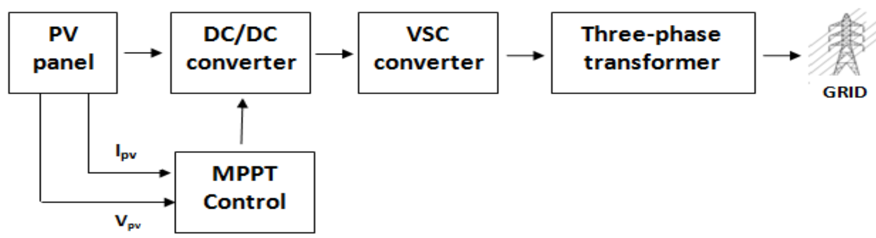



Figure 1. Diagram of a grid-connected PV system

### 2.1. PV Solar Module

A photovoltaic cell is made of semi-conductor materials and converts light energy directly into electrical energy. It is based on physical phenomenon called photovoltaic effect. To produce more power, the solar cell is assembled to form a module. The serial connections of several cells increase the voltage, while the implementation in parallel increase the current [9].

Electrically, each cell is represented as follows in Figure 2 [10]:

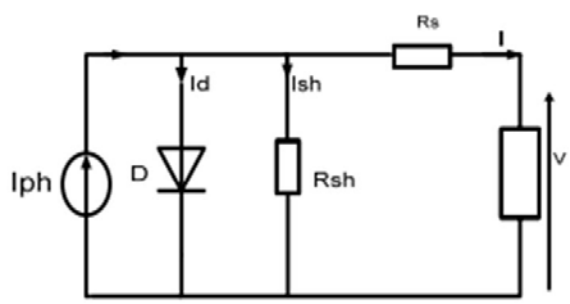



Figure 2. Photovoltaic cell equivalent circuit

The final equations of the photovoltaic panel model are:

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

$$I_{pv} = I_{ph} - I_0\left(e^{\frac{q\times(V_d+I\times R_S)}{K\times T}} - 1\right) - \frac{(V+I\times R_S)}{R_{sh}} \tag{2}$$

with:

$$I_{ph} = (I_{scr} + K_i \times \Delta T) \times S \tag{3}$$

$$I_d = I_0 \times N_{pp}\left(e^{\frac{q\times\left(V+I\times R_S\times\left(\frac{N_{ss}}{N_{pp}}\right)\right)}{K\times T}} - 1\right) \quad (4)$$

$$I_0 = I_{rr}\left(\frac{T_c}{T_r}\right)^3 e\left(\frac{qE_G}{Kn}\left(\frac{1}{T_r} - \frac{1}{T_c}\right)\right) \quad (5)$$

$$I_{sh} = \left(\frac{V_{pv}+R_S\times \mathrm{I_{pv}}}{R_{sh}}\right) \quad (6)$$

Table 1. Expression of symbols

| Used Parameters in above Equations | |
|---|---|
| $V$, $I_{pv}$ Output Voltage, Current (V, A) | $I_{rr}$ Saturation Current at $T_r$ |
| $I_{ph}$ Light Generated Source | $S$ Solar Irradiance (W/m$^2$) |
| $T_c$ Cell Temperature (K) | $T_r$ Reference temperature |
| $I_d$ Diode Current | $n$ Ideality factor |
| $q$ Charge of an electron | $E_G$ Band-Gap Energy of the material |
| $I_{scr}$ Short-Circuit Current at Reference Condition | $K$ Boltzmann's constant |
| $K_i$ Short-Circuit Temperature coefficient | $I_0$ Saturation current |
| $N_{pp}$ Number of cells in parallel | $N_{ss}$ Number of cells in series |

The PV module adopted in this study is 100-kW uses 330 SunPower modules (SPR-305E-WHT-D) consists of 96 polycrystalline silicon solar cells electrically configured as five series strings of 66 cells each [11]. The manufacturer specifications for one module are:
- Number of series-connected cells: 96.
- Open-circuit voltage: Voc= 64.2 V.
- Short-circuit current: Isc = 5.96 A.
- Current and voltage at maximum power: Imp= 5.58 A, Vmp =54.7 V.

### 2.2. Boost converter DC/DC

The boost converter is also called a step-up converter it generates a higher output voltage than the input. The suggested converter in Figure 3 is similar to the classical boost converter, but differs only in the integration of a PID controller which is extensively used in many practical applications for better performance. It consists of an input voltage source, a switch, an inductor, a diode for protecting the PV module against negative current that could damage it and a capacitor [12].

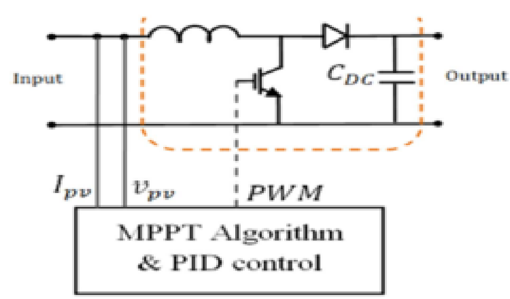



Figure 3. Boost Converter Modeling

## 3. MAXIMUM POWER POINT TRACKING (MPPT)

In the last two decades, numbers of different MPPT have been developed [13]. In our study, three MPPT techniques have been selected for the purpose of comparison:
- Incremental Conductance (INC)
- Perturbation and Observation (P&O)

- Fuzzy Logic (FL)

### 3.1. Incremental Conductance (INC)

The Incremental Conductance can determine if the MPPT has reached the MPP and stop disrupting the operating point.

It is based on the knowledge of the value of the conductance $G = \frac{I}{V}$ and on the increment of the conductance ($\mathrm{d}G = \frac{\mathrm{d}I}{\mathrm{d}V}$) to deduce the position of the operating point relative to the point of maximum power.

Figure 4 shows that the slope of the P-V power curve is zero at the MPP, increasing to the left of the MPP and decreasing to the right of the MPP.

The basic equations of this method are:

$$\frac{\mathrm{d}I}{\mathrm{d}V} = -\frac{I}{V} \text{ at MPP} \tag{7}$$

$$\frac{\mathrm{d}I}{\mathrm{d}V} > -\frac{I}{V} \text{ left of MPP} \tag{8}$$

$$\frac{\mathrm{d}I}{\mathrm{d}V} < -\frac{\mathrm{I}}{\mathrm{V}} \text{ right of MPP} \tag{9}$$

Where $I$ and $V$ are the PV array current and voltage respectively [14].

From (7) - (9), it is obvious that when the ratio of change of the conductance ($\mathrm{d}G$) is greater than the opposite of the conductance ($-G$), the duty cycle is decreased. On the other hand, if it is smaller than the opposite of the conductance ($-G$), the duty ratio is increased. This process is repeated until reaching the point of maximum power [15]. The follow-up of the maximum power point requiring the procedure above is indicated in Figure 5.

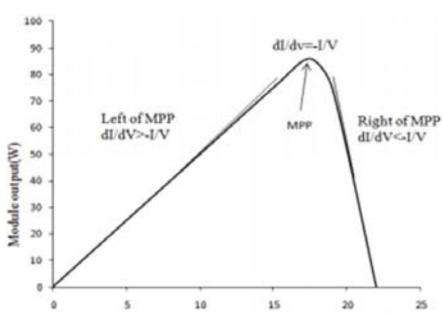



Figure 4. Basic idea of the Incremental Conductance method on a P-V curve of a Solar Module

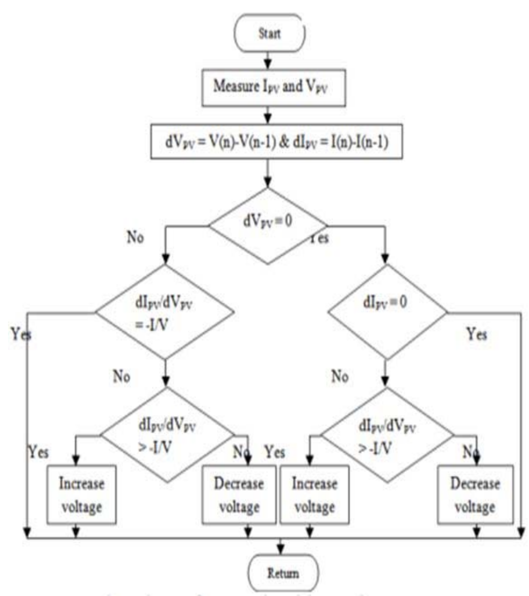



Figure 5. Organization chart of the INC algorithm

### 3.2. Perturbation and Observation (P&O)

P&O algorithm are widely used in MPPT because of their simple structure and their few measured parameters which are required. As its name indicates, the concept of the algorithm is by increasing or decreasing the voltage of the PV array, then observing the effect of this change on the PV generated power [16]. The perturbation is continued in the same direction when the power increases due to the perturbation. After the peak power is reached the power at the MPP is zero and next instant decreases and hence after that, the perturbation reverses as shown in Figure 6 [17].

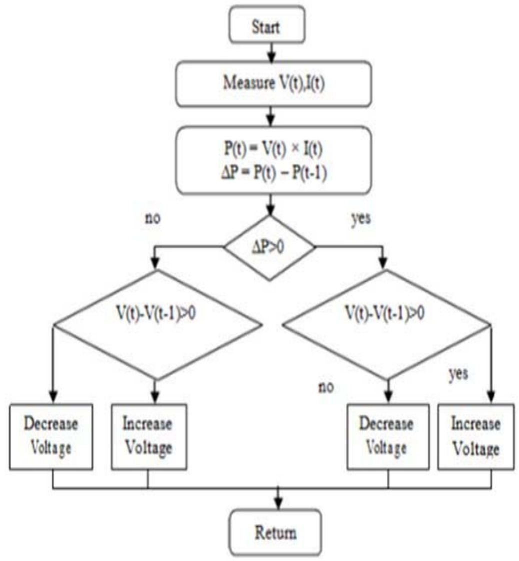



Figure 6. Organization chart of the P&O algorithm

### 3.3. Fuzzy Logic (FL)

Recently in PV systems, fuzzy logic controllers have been introduced in the tracking of the MPP.

They have the advantage to be robust and relatively simple to design as they do not require the knowledge of the exact model [18]. In particular, this command is better adapted to non-linear systems.

As represented in Figure 7 the operation of this algorithm is done in three blocks: fuzzification, inference and defuzzification.

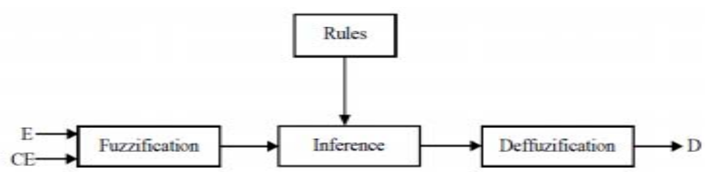



Figure 7. General scheme of a fuzzy controller

Fuzzification transforms input variables into linguistic variables or fuzzy variables.

The Fuzzy controller has two inputs and one output.

The two input variables are the E error and the CE error change defined by:

$$E(k) = \frac{P_{pv}(k) - P_{pv}(k-1)}{V_{pv}(k) - V_{pv}(k-1)} \quad (10)$$

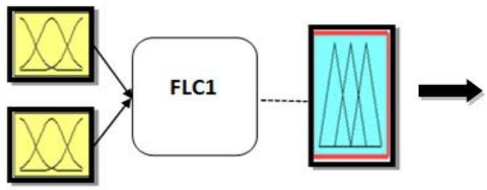
$$CE(k) = E(k) - E(k-1) \quad (11)$$

Where $P_{pv}(k)$ and $V_{pv}(k)$ are respectively the power and the voltage of the photovoltaic generator.

The input $E(k)$ shows if the operating point of the load at time k is located to the left or right of the point of maximum power on the PV characteristic, while the input $CE(k)$ expresses the direction of this point [19]. Figure 8 presents the Fuzzy inference using the Mamdani method, and defuzzification uses the center of gravity to calculate the output of the fuzzy controller which is the duty cycle [11]:

$$D = \frac{\sum_{j=1}^{n} u(Dj)Dj}{\sum_{j=1}^{n} u(Dj)} \quad (12)$$

The control rules are shown in the table below with $E$ and $CE$ as inputs and $D$ as output.




| CE / E | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | ZE | ZE | PB | PB | PB |
| NS | ZE | ZE | PS | PS | PS |
| ZE | PS | ZE | ZE | ZE | NS |
| PS | NS | NS | NS | ZE | ZE |
| PB | NB | NB | NB | ZE | ZE |

Figure 8. Structure of inference rules

## 4. SIMULATION AND RESULTS

Our study is based on a 100-kW photovoltaic generator that is connected to a 25 kV grid via a DC-DC boost converter and a three-phase voltage source converter (VSC).

Maximum Power Point Tracking (MPPT) is implemented in the boost converter by means of a Simulink model using different algorithms.

The studied model contains the following components:

- **PV array** delivering at 1000 W/m2 sun irradiance a maximum of 100-kW.
- **5-kHz DC-DC Boost converter** increasing voltage from PV natural voltage from 273 V DC at maximum power to 500 V DC. The operating cycle of the switching is optimized by an MPPT controller which automatically varies the duty cycle to generate the voltage required to extract the maximum power.
- **3-level 3-phase VSC**: The VSC converts the 500 V DC link voltage to 260 V AC and keeps unity power factor. The VSC control system uses two control loops: an internal control loop which regulates Id and Iq grid currents and an external control loop which regulates DC link voltage to +/- 250 V. Id current reference is the output of the DC voltage external controller. To maintain unity power factor, Iq current reference is set to zero. The voltage outputs Vd and Vq of the current controller are converted into three modulation signals Uabc_ref used by the PWM generator.
- **10-kvar capacitor bank** filtering harmonics produced by VSC.
- **100-kVA 260V/25kV three-phase coupling transformer.**
- **Utility grid** (25-kV distribution feeder + 120-kV equivalent transmission system).

### 4.1. Simulation of grid connected PV module with INC as MPPT algorithm

In this simulation, the PV array model contains an algebraic loop. This algebraic loop is required to get an accurate and iterative solution of the PV model when large sample times are used. The simulation of grid connected PV module with INC as MPPT algorithm result is shown Figure 9 to Figure16.

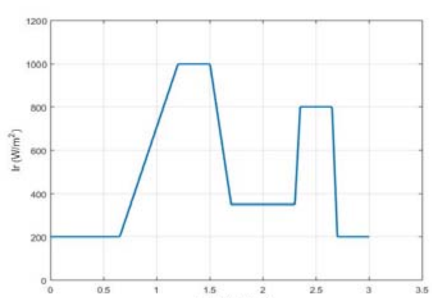



Figure 9. Variation of solar radiation vs time

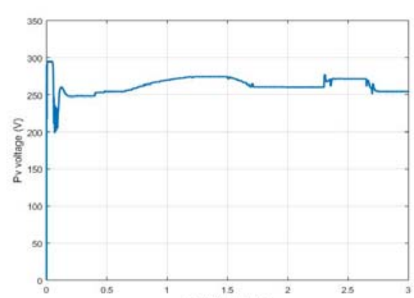



Figure 10. Variation of PV voltage vs time

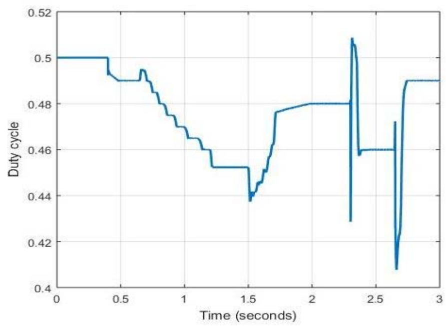



Figure 11. Variation of Duty Cycle vs time

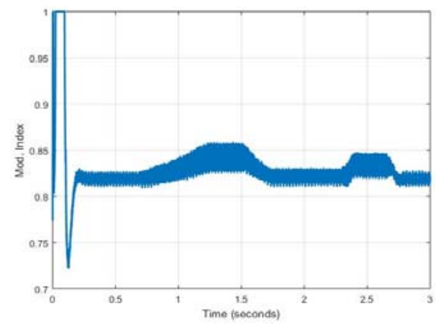



Figure 12. Modulation Index vs time (Mod.Index)

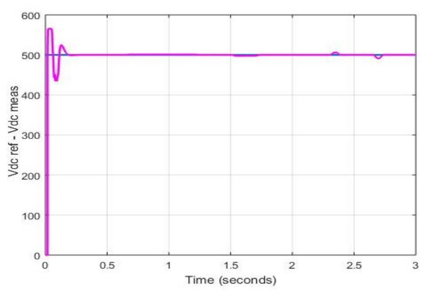



Figure 13. Measured Voltage and Reference Voltage vs time (Vdc ref - Vdc meas)

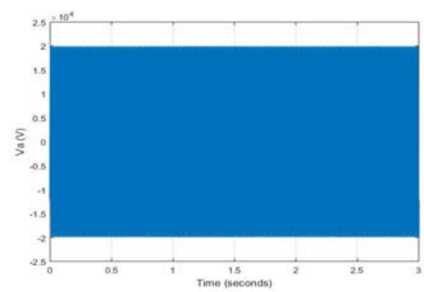



Figure 14. Variation of voltage (Va) at the utility grid vs time

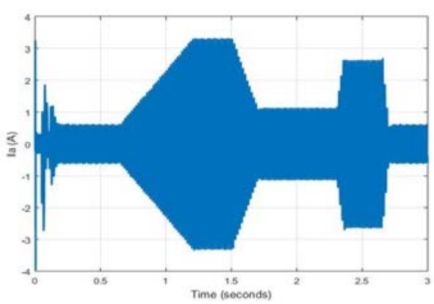



Figure 15. Variation of voltage (Ia) at the utility grid vs time

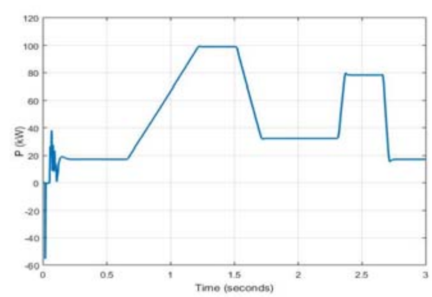



Figure 16. Variation of the power output at the utility grid vs time

**4.2. Simulation of grid connected PV module with P&O as MPPT algorithm**

The main difference between this model and the previous model is in the way that DC-DC boost converter and three phases VSC are modeled. In this model, the boost and VSC converters are represented by equivalent voltage sources generating the average AC voltage over one cycle of the switching frequency.

This model allows using much larger time steps than the detailed model (50 microseconds v/s 1 microsecond), which allows a much faster simulation. The simulation of grid connected PV module with P&O as MPPT algorithmis shown Figure 17 to Figure 24.

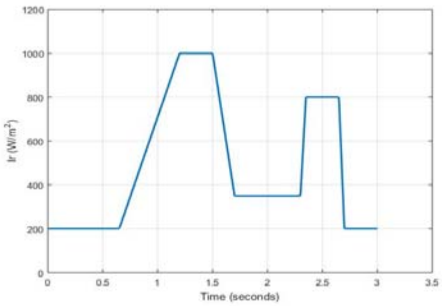



Figure 17. Variation of solar radiation vs time

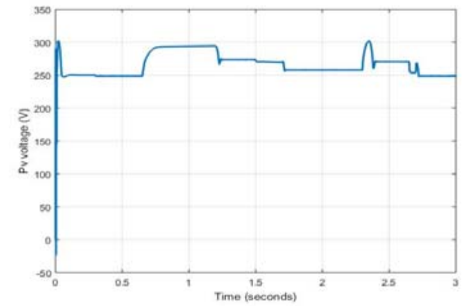



Figure 18. Variation of PV voltage vs time

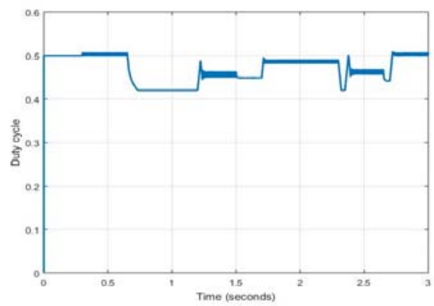



Figure 19. Variation of Duty Cycle vs time

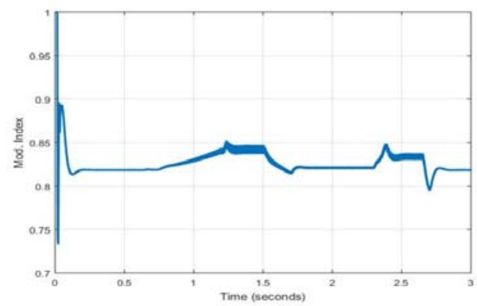



Figure 20. Modulation Index vs time (Mod.Index)

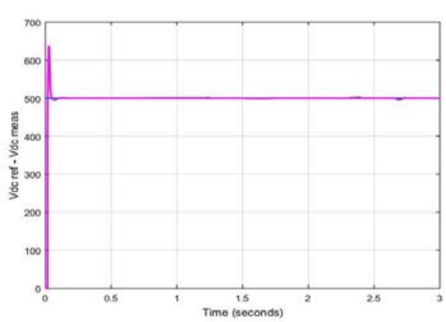



Figure 21. Measured Voltage and Reference Voltage vs time (Vdc ref - Vdc meas)

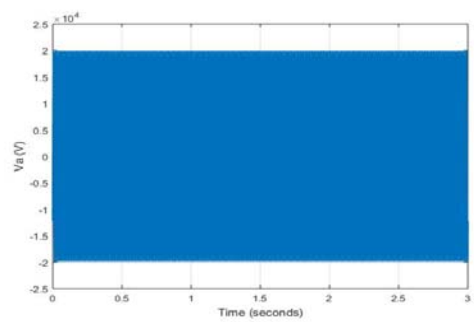



Figure 22. Variation of voltage (Va) at the utility grid vs time

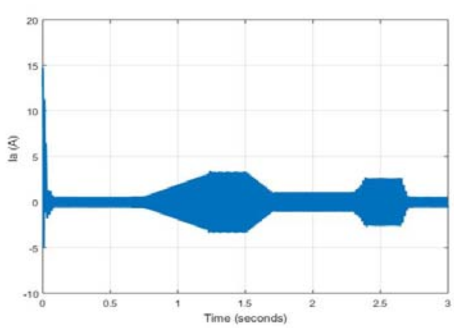



Figure 23. Variation of voltage (Ia) at the utility grid vs time

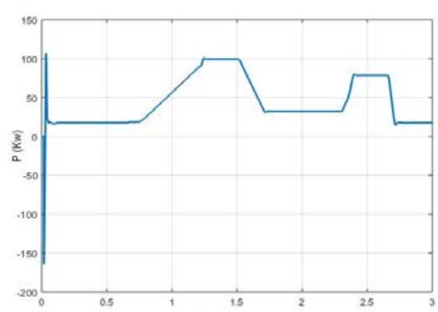



Figure 24. Variation of the power output at the utility grid vs time

**4.3. Simulation of grid connected PV module with LF as MPPT algorithm**

This simulation is the same one used when we simulated P&O as MPPT algorithm. The result of the simulation is shown in Figure 25 to Figure 32.

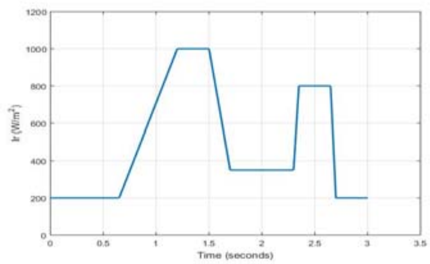



Figure 25. Variation of solar radiation vs time

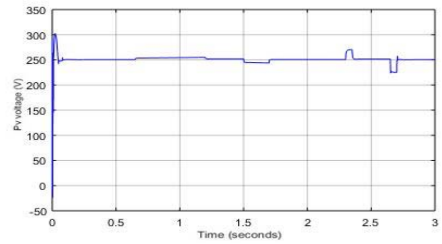



Figure 26. Variation of PV voltage vs time

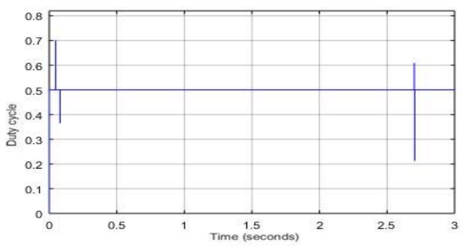



Figure 27. Variation of Duty Cycle vs time

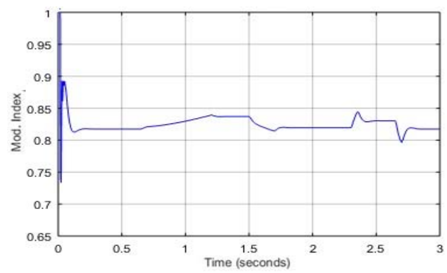



Figure 28. Modulation Index vs time (Mod.Index)

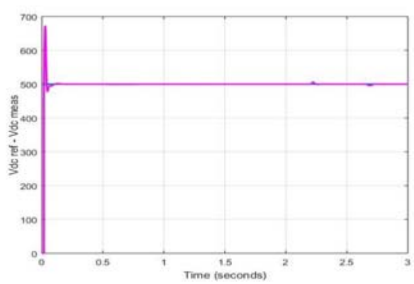



Figure 29. Measured Voltage and Reference Voltage vs time (Vdc ref - Vdc meas)

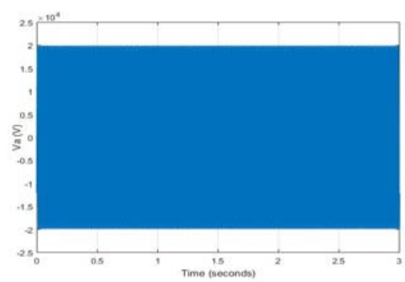



Figure 30. Variation of voltage (Va) at the utility grid vs time

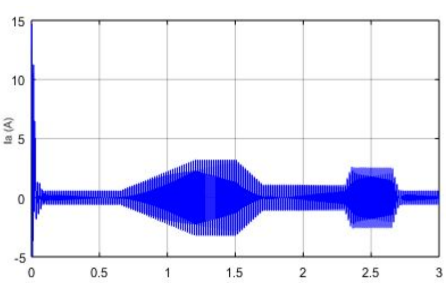



Figure 31. Variation of voltage (Ia) at the utility grid vs time

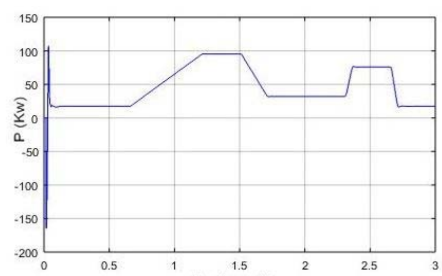



Figure 32. Variation of the power output at the utility grid vs time

## 5. COMPARATIVE STUDY OF RESULTS:

Many algorithms are developed in order to maximize the efficiency of the PV system and to extract the maximum possible power from it. These algorithms differ in their efficiency, accuracy, reliability, and complexity.

The P&O algorithm is often used for the reason that it is easy to implement. This strongly depends on the initial conditions and oscillations around the PPM because the search must be repeated periodically to force the system to oscillate around the PPM. From the simulation results shown above, it can be seen that P&O algorithm under cloudy skies had a significantly higher efficiency than incremental conductance.

The noticeable increase in the efficiency of the INC algorithm is due to its ability to overcome the disadvantages of the P&O algorithm, to follow fast atmospheric changes and avoid oscillations around the MPP. The output voltage using the INC method varies less when the atmospheric conditions vary rapidly and generate more power with the same variable illumination values as P&O, but its development remains more complex.

The results obtained for this energy conversion system, show that by using the MPPT fuzzy controller, there is a compromise between rapidity in transient regime and stability in the steady state.

This command has very good performance; it is more flexible for nonlinear systems and allows to find the point of maximum power in a very short time compared to the other methods INC and P & O.

It improves the responses of the photovoltaic system, not only does it reduce the response time at the point of maximum continuous power, but it also eliminates the fluctuations around this point and converges rapidly while reducing the power losses of the photovoltaic panel.

Referring to [20] and other works [21,22], our results are verified. It is proved that the Fuzzy Logic method has better performance than the other techniques, it is featured by a good rapidity and accuracy, but the main limitation of this algorithm is the complexity of implementation.

## 6. CONCLUSION

This paper describes the 100-kW solar PV grid connected solar photovoltaic system designed in MATLAB/Simulink and observes the performance evaluation of the system. Solar PV system is taken as a primary resource.

The pursuit of the optimal point is well accomplished in all three cases, but in different ways, making one more optimal than the other.

It is shown that the overall power of the photovoltaic solar panel increases with the increase of the solar irradiation and the results obtained with a Fuzzy Controller are better than those obtained with INC and P&O, it also proved that it has better performances, fast response time, very low steady-state error, and is robust to different variations in atmospheric conditions.

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